10.2 Current and Future Changes

Continuous and discontinuous permafrost

While global and climatic changes are ongoing processes in the earth system, scientists have several reasons for concern. Global climate has warmed since the mid to late 1800s (Hansen and Lebedev 1987). In the circumpolar Arctic, permafrost has generally warmed, particularly in Russia, China, Alaska, and western Canada. In Alaska, the continuous permafrost warmed 2 to 4°C over the last century (Lachenbruch and Marshall 1986). Indications are that the discontinuous permafrost also warmed during this time period (Osterkamp and Romanovsky 1997). Climate and permafrost in many areas of the circumpolar Arctic continue to warm particularly in Alaska and parts of Eastern Russia in the Bering Sea region (Fig. 10.6).

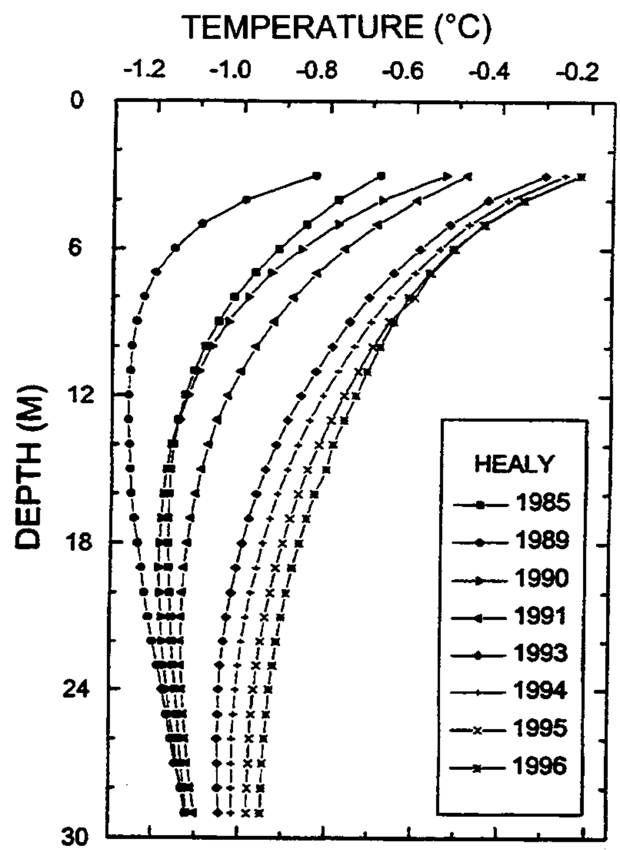

Figure 10.6. Temperature profiles in permafrost at a site near Healy, Alaska showing the warming of the permafrost that has occurred since 1989. Thermokarst has developed in this area in response to the warming.

All of our permafrost research sites along a North-South transect from Prudhoe Bay to Glennallen warmed between the mid to late 1980s and 1996 (Osterkamp and Romanovsky 1996,1997). In the continuous permafrost region, the warming ranges up to 4°C in the active layer and at the top of the permafrost. In the discontinuous permafrost region, the warming is typically between 1 and 2°C. At some of the sites, permafrost is presently thawing at both the top and bottom.

Thawing of ice-rich permafrost has been identified as the primary problem for infrastructures. Continued warming will cause additional permafrost to thaw. The effects of thawing ice-rich permafrost in response to climatic change will be superimposed on the effects associated with the infrastructure. Current climate scenarios predict 5°C additional warming in the next half century for northern regions. These results are causing considerable concern about the future of permafrost in Alaska and the impacts associated with warming and thawing of the permafrost.

An expected climate scenario for the Bering Sea region has been outlined by Weller et al. (Chapter 2) which indicates about a 5°C warming with the winter warming larger than the summer warming and with more precipitation in both the summer and winter. Air temperatures and depth of the snow cover influence permafrost temperatures. If the depth of the snow cover increases with no change in air temperatures then permafrost will warm. If there is an increase in air temperatures as well as depth of the snow cover then the effects of this climatic change will be magnified over that of an increase in air temperatures only.

The impacts of a climatic warming of this magnitude (5°C) will differ considerably for the continuous and discontinuous permafrost zones of the earth. A central paradigm of current research is that thawing permafrost will result in the release of carbon deposits frozen in the permafrost and that these deposits will lead to increased fluxes of trace gases to the atmosphere creating a positive feedback loop. Figure 10.7 is a schematic showing some of the relationships between climate, soil and permafrost, biota and human activities.

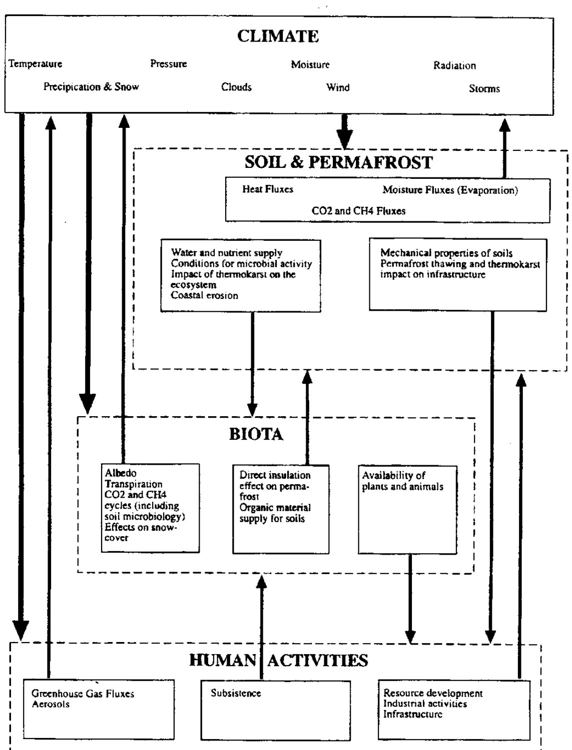

Figure 10.7. Schematic diagram showing relationships between climate, soil and permafrost, biota and human activities.

Some of the continuous permafrost has warmed almost continuously since the mid-1980s. However, mean surface temperatures are still typically colder than -5°C so that only warming of the permafrost is expected with no widespread thawing anticipated except that which will be associated with localized sites such as south facing slopes, with possible thickening of the active layer and with two-dimensional heat flow effects as in the banks of rivers and lakes. Increases in the depth of the snow cover would lead to a greater warming of the permafrost than indicated by a warming of air temperatures alone.

Thaw lakes, eolian activity, vegetation, and coastal, geomorphic and hydrologic processes in this region may be sensitive to climatic warming (Brown and Andrews 1982). If the active layer thickens by thawing of the near-surface permafrost, this will result in the release of carbon currently stored (frozen) in the permafrost leading to enhanced production of carbon dioxide and methane gases. Where the permafrost is ice-rich, this thawing will produce subsidence of the ground surface resulting in thermokarst terrain commensurate with its ice contents and thickness of the new active layer. This thermokarst would result in some damage to the ecosystem.

Permafrost temperatures in the discontinuous permafrost zone south of the Yukon River in Alaska and on the south side of the Seward Peninsula are very warm, typically within 2°C of thawing (Osterkamp 1994). Data from a north-south transect of Alaska shows that all of the sites south of the Yukon River warmed between 1989 and 1996, a period with unusually heavy snow fall (Osterkamp and Romanovsky 1997). The warming ranged from > 1/2°C to about 2°C at the permafrost table. At some of the sites, permafrost is presently thawing at both the table and base in response to this warming.

If these data can be extrapolated to other areas, then it can be inferred that the discontinuous permafrost south of the Yukon River and on the south side of the Seward Peninsula has recently warmed and that much of it is currently thawing.

The impacts of thawing permafrost on human activities and the physical environment will differ depending on the permafrost ice content.

- If the permafrost is not ice-rich, warming and thawing of the permafrost will be limited to thermal effects and to the effects of converting the ice to water. Impacts on the infrastructure will be relatively minimal.
- Where the permafrost contains massive ground ice or is ice-rich, extensive thaw settlement (resulting in thermokarst) is expected. The magnitude of this thaw settlement has been observed to exceed 5m and to reach 10m, in some cases, of vertical settling of the ground surface. Induced thaw settlement is presently responsible for damage to houses, roads, airports, military installations, pipelines, and other facilities founded on ice-rich permafrost.

Engineering Concerns in Permafrost Terrain

The surface vegetation (moss) and underlying organic soil are usually destroyed or severely damaged during construction. This vegetation and organic soil insulates the permafrost from the effects of summer warming and its removal causes the permafrost to warm by several degrees and the active layer to become deeper or for a talik (thawed layer) to form. Once a talik forms the permafrost thaws continuously (throughout the year) from the top downward inducing thaw settlement if it is ice-rich. A heated structure on the permafrost will enhance thawing of the permafrost.

Induced thaw settlement is presently responsible for damage to houses, roads, airports, military installations, pipelines, and other facilities founded on ice-rich permafrost. Any natural increase in the MST of permafrost and subsequent thaw settlement would create severe maintenance problems for facilities in Alaska adding to effects already being observed. Some structures, airports and roads might have to be abandoned if funds are not adequate to continue repairs (Esch and Osterkamp 1990).

The physical and mechanical properties of permafrost are generally temperature dependent and, for warm permafrost (permafrost within one or two degrees of thawing), depend strongly on temperature. Most of the engineering concerns related to a climatic warming can be classified into those related to an increase in permafrost temperatures, those related to increases in the active layer thickness (annual thaw depth), and those related to the degradation of the permafrost.

Engineering concerns related to a general warming of the permafrost result primarily from the decrease in mechanical strength, especially compressive and shear strengths, and the increase in creep rates of frozen ice-rich soils. Ad-freeze bond strengths between permafrost and piles or structures are also strongly temperature dependent. As an example, piling designed for a permafrost temperature of -4°C will experience a 70% loss in load capacity if the permafrost temperature rises to -1°C. Because of the presence of unfrozen soil pore water solutions in warm permafrost, the problems may be expected to be even more severe as the temperature of warm permafrost approaches the thawing point. Reliable methods of predicting permafrost temperatures over the life of a facility and information on the physical and, especially, the mechanical properties of warm permafrost are needed to help evaluate these problems.

Systematic increases in the thickness of the active layer may be expected to lead to thaw settlement of underlying ice-rich permafrost. Increased frost heaving during winter and increased frost heave forces on pilings may also be expected when the active layer thickness increases. Better understanding of the processes associated with active layer development are needed to evaluate this problem. The effects of saline soil solutions found in coastal and other areas on freezing and thawing in the active layer need to be understood.

Active layer thicknesses generally depend, among other factors, on the amplitude, timing and duration of temperatures during the thaw season. Therefore, climatic predictions must address changes in seasonal temperatures to be helpful in evaluating active layer problems.

As noted above, continued climatic warming and increases in the depth of the snow cover will eventually cause much of the discontinuous permafrost in Alaska to thaw. Thawing begins with thickening of the active layer and, eventually, a talik (a layer of ground that remains unfrozen throughout the year) develops when the thaw depth exceeds the depth of seasonal freezing. Continued thawing at the permafrost table results in continued thaw settlement in ice-rich permafrost. The effective length of a piling in the permafrost will decrease while the frost heave force on the piling reaches its maximum. Thermokarst terrain, increased downslope soil movement and landslides, and other terrain features common to degrading permafrost may be expected to appear (Osterkamp 1982). Roads, airfields, railway embankments and other foundations on degrading permafrost may be subject to continuing deformations as a result of the thaw settlement. Accurate predictions of the climate-permafrost response at a regional level are needed to assess the timing, duration, and severity of these problems. New and innovative engineering designs will be required to solve them.

Ecosystems effects

In areas of ice-rich permafrost, thaw settlement and the development of thermokarst will destroy the substrate on which the current ecosystems rest dramatically changing the nature of the ecosystems. It has been observed to result in damage to the ecosystems and sometimes in the total destruction of the ecosystems and their conversion to other types of ecosystems. Most of the following impacts have already been observed and are not speculation.

- Destruction of trees and reduction in area of boreal forests (Fig. 10.5 and 10.6).
- Expansion of thaw lakes, grasslands and wetlands (Fig. 10.6).
- Destruction of habitat for caribou and terrestrial birds and mammals.
- Increased habitat for aquatic birds and mammals.
- Increased rates of coastal and riverbank erosion (Fig. 10.4).
- Clogging of salmon spawning streams with sediment and debris (Fig. 10.4).
- Increased slope instability, landslides, erosion.
- Talik development with increased depth to water table.

The infrastructure also has some effects on the landscape and biota which may change as a result of climatic warming. For example, small birds are known to migrate along north-south highways. In areas of low hydrologic gradients, the roadbed can dam the surface water flow causing the death of trees and thereby modify the ecosystem on that side of the roadbed.

In the short term, ecosystems will change dramatically as ground surface collapse up to several meters will cause soil disruption, changes in topography (thermokarst), local flooding, tree die-off, and forest stand re-initiation. Resulting decreases in slope stability will increase erosion, mass wasting and sediment loading of streams.

Longer term consequences depend on depth of permafrost, hydrologic changes via modified local topography, greater infiltration, and less runoff, and resulting changes in vegetation colonization and succession. Deeply frozen soil may take decades to thaw, lengthening the transition period and delaying the attainment of any new steady state. Following thaw of near-surface permafrost, soils without water tables perched over permafrost may be drier than they are currently, likely promoting fire and fire-tolerant species in lieu of white spruce.

In the Tanana Flats south of Fairbanks, for example, Jorgensen (1997 unpublished data) has observed that graminoid species replace birch and spruce in areas temporarily flooded by thermokarst. Poorly drained areas may remain flooded longer, resulting in larger and more numerous wetlands and thermokarst ponds. Permafrost thaw ultimately will have beneficial results as well. Because of greater infiltration and less water table perching, watersheds containing only unfrozen soil will be less prone to flash flooding during rainstorms. Where sufficient moisture is available, warmer soils will promote greater productivity of newly established forest stands. Engineering of roads and structures will be easier and less expensive after permafrost has completely thawed.

Other impacts

Other impacts that were considered included increased snow fall, increased frequency of storm events and increased run-off, glaciers and frost heaving. Increased snow fall would decrease visibility, increase snow removal costs and possibly lead to increased frequency of road and airport closures. Increased run-off from storms, increased precipitation and increased flooding would create problems for bridges and culverts and drainage structures. This would add to the problem of increased discharge from glaciers. Wetter soils may lead to increased frost heaving of structures. However, these potential impacts are considered to be of minor importance compared to the major impacts associated with thawing ice-rich permafrost.

10.3 Uncertainties

Uncertainties associated with the above potential impacts are primarily related to the predictions of current climatic models, a lack of knowledge of current conditions and a lack of information on the economic impacts of thermokarst on the infrastructure. The spatial scales of current climatic models are too large for use by design engineers who need information on temperature, precipitation and wind at local scales for design purposes. Information on current conditions, particularly climate and permafrost is sparse in Alaska. There are few primary climate stations in Alaska, an area quite large compared even to the size of the contiguous U. S. Information on temperatures in permafrost on the Alaskan side of the Bering Sea come from two sites, one at Nome and one at Bethel. The next closest sites are more than 400 miles to the east.

Costs of thawing permafrost do not appear to have been evaluated. These costs appear to be staggering. Some idea can be obtained by considering that the original cost of the Trans-Alaska Pipeline was $900 million dollars for a conventionally built pipeline buried in the ground. The final cost was over $7 billion dollars, an eight-fold increase, largely because of the presence of unavoidable ice-rich permafrost along the route. Another example is a 1 km length of Farmer's Loop Road adjacent to the University of Alaska at Fairbanks built on ice-rich permafrost where in excess of $5 million dollars has been spent on maintenance and reconstruction of the road without solving the problems.

Thermokarst could lead to the abandonment of villages in low-lying areas. Relocation of these villages would be a major economic impact. The DOTPF had to move their maintenance facility at Gardiner Creek because of damage to the buildings by thawing and settling of the ice-rich permafrost.

Direct costs to the public of thawing ice-rich permafrost have also not been evaluated. As noted previously, some homes have been damaged or abandoned because of thermokarst. There are increased costs associated with shorter airport runways. There is clearly lost time and increased wear and tear on vehicles because of rough roadways and it is believed that some lives may have been lost because of rough roadways.

If the climate does not change from the current condition where air temperatures in Alaska have been warmer for the last twenty years (since 1976) than the previous twenty years and where snow cover has been unusually thick during the last decade (Osterkamp and Romanovsky 1997), then permafrost will continue to thaw. The data base on permafrost temperatures is too sparse to predict the distribution of this thawing.

10.4 Additional Research Needed

Climate

Thorough analyses of recorded climatic data in the Bering Sea region is needed to assess the timing, magnitude and distribution of recent climatic changes and those during the last century, particularly changes in air temperatures and snow depth. Remote stations that are not influenced by local anthropogenic changes need to be established. Climate models should be verified using data through the mid-1970s and should be capable of predicting the changes that occurred at that time. Improved high resolution climatic models need to be developed to improve climatic change scenarios, to improve predictions of seasonal changes in air temperatures and precipitation and to improve the spatial resolution of the models for engineering design purposes.

Permafrost

Investigations of the current and past state of the permafrost in the Bering Sea region are needed to develop an improved understanding of how permafrost has responded and is responding to changes in climate over the last century. The processes by which permafrost thaws are poorly understood. For example, data on heat and mass flow during talik formation and the creation of thermokarst are almost nonexistent. More information is needed on the distribution of ice-rich permafrost and on the formation of thermokarst since thermokarst is responsible for most of the engineering concerns in permafrost regions.

Engineering

Engineers need to know the state of the permafrost at the project site and what will happen to the permafrost during the life of the project. Information on the properties of warm and thawing permafrost will be needed. At some point, strategy should shift from mitigating the effects of thawing permafrost to that of causing the permafrost to thaw. Methods for pre-construction thawing of the permafrost need to be identified and developed. New and innovative engineering designs for construction on warm and thawing permafrost will be required. Geophysical methods for detection of ground ice and potential thermokarst areas are available (Kawasaki and Osterkamp 1985). Policies and personnel for their use should be developed within DOTPF.

Policy and Economics

Current policies of the DOTPF and federal and state agencies for construction on permafrost terrain carry associated costs and have a direct impact on the public. These policies, costs and impacts need to be identified and documented. For example, case studies of pipeline, road and airport design, construction, repair and reconstruction are needed to define the costs and impacts of policies during a climate warming scenario and to identify new policies that would reduce these costs and impacts.

10.5 Mitigation and Adaptation Measures

Research is needed to identify the problems, impacts and costs of a climatic warming associated with maintaining the public infrastructure and develop ways and means to mitigate the negative effects of a climatic warming.

Programs are needed to inform the public, develop an awareness of the potential problems and provide aid in identifying problems and solutions not only in the major population centers but also in the many villages in rural Alaska.

State and federal agencies should identify areas, sites and facilities that may be subject to the negative impacts of climatic change. These should also be rated according to the severity of the impacts expected for them.

Changes in current policy of the DOTPF and federal government could help to mitigate the effects of thawing ice-rich permafrost. For example, purchase of the necessary land and easements for a construction site or route selection is currently done just prior to the construction project. This policy does not allow sufficient time to carry out inexpensive mitigation measures prior to construction. One method would be to strip the vegetation and organic soil at the ground surface five years or more prior to construction to let the permafrost thaw naturally. Installation of a gravel pad or roadbed for summer use could be done during this period. This method would allow the location of the ice-rich permafrost to be determined and the top several meters to thaw naturally.

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